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TECHNICAL MEMORANDUM 1144

AMMUNITION GROUP

ESTABLISHMENT OF DESIGN CRITERIA FOR PROTECTIVE STRUCTURES AND PROCESSING OF EXPLOSIVES

BY

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DOVER, NEW JERSEY

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FOREWORD

The material contained in this Technical Memorandum was the subject of a presentation made to the Loading Section--Bomb, Warhead and Artillery Ammunition Division, American Ordnance Association on 18-19 April 1962 at Picatinny Arsenal and to the 7th meeting of the Integration Committee on Explosives and Propellants on 10-11 October 1962 at Radford Arsenal, Virginia, and was published in the meetings' official minutes. A preliminary version was presented by Mr. C.E. McKnight to the Explosives Pressing Steering Committee meeting held at Picatinny Arsenal on 11-12 April 1962.

ADDENDUM

Subsequent to the presentation of this paper certain revisions have been made to the relationships defining blast reflection factors used in the illustrative examples. Based on these revisions, reflection effects as described in this paper are conservative. Moreover, these revisions do not alter the design principles discussed in this paper.

Picatinny Arsenal has been engaged in a broad program aimed at establishment of more realistic safety design criteria for Explosive Manufacturing and Storage Facilities.

Figure 1 - is a schematic representation of the phases of our work, which are either completed, in progress, or to be shortly initiated. As can be seen from the chart, Phase I deals with prevention of propagation and personnel injury due to pure blast effects. Phase II deals with the effects of primary fragment impact resulting from rupture of the donor explosive casing in causing explosion propagation. Phase III deals with the development of design criteria for protective structures, for prevention of explosion propagation and personnel injury. These analytical phases of our overall program were essentially completed. At present we are in the process of confirming and supplementing these developed relationships by running confirmatory tests on the primary fragment effects (which are in progress), and on protective wall design (which will be initiated shortly). At the same time we are preparing a proposed supplement to the Ordnance Safety Manual dealing with protective design.

At previous meetings of the Loading Section papers were presented dealing with the first two phases of this overall program, namely propagation from blast and primary fragments.

This paper deals with the 3rd phase of our overall program, namely development of design criteria for protective structures, for prevention of propagation of explosion into the acceptor charge and personnel injury.

Although the Ordnance Safety Manual gives guide lines for the establishment of barricades and substantial dividing walls which have been used effectively for many years, a detailed quantitative procedure for assessing the degree of protection which may be expected from existing protective walls or designing new walls is not currently available. Furthermore, although a substantial amount of work has been done in the development of protective wall design criteria, based upon existing data and theoretical considerations, this work has been primarily concerned with relatively distant effects of explosions where a plane wave approach or uniform loading at each section of the wall may be employed. Although situations of this sort are of interest to Ordnance, the majority of actual cases are concerned with close-in effects where explosives are in relatively close proximity to the protective wall. Because of the non-uniformity of wall loading in such cases application of the plane wave theory is not valid.

Recognizing the need for the development of more quantitative and more precise safety design criteria, Picatinny Arsenal initiated a broad program, one of the ultimate objectives of which was the establishment of structural design criteria for protective walls.

In simplest terms, a typical explosive system for which structural design criteria must be considered consists of a donor explosive charge (e.g. weapon or processing vessel) which produces the damaging output, an acceptor (e.g. another explosive charge, personnel or equipment) the sensitivity of which determines what degree of output it can tolerate, and the intervening protective wall and/or distance. The overall design approach, therefore, was divided into three separate but related areas, namely donor effects, wall response and acceptor effects.

Let us first consider the donor charge which produces primary fragments and blast acting on the protective wall. It is first necessary to determine blast characteristics of the donor explosion and to determine the pressure and impulse patterns which may be formed on the surface of a substantial dividing wall. The determination of these pressures and impulse patterns is dependent upon the location of the detonation in relation to the wall. Three basic locations may be considered as indicated on Figure 2:

First, the donor may be considered to be in free air with the blast wave propagating out from the center of the explosion and striking the wall.

Secondly, the donor may be placed at such a location in relation to the wall that the wall is subjected to the combined effects of free air and reflected pressures.

Finally, the charge location may be such that the entire wall is subjected to a uniform blast load.

In a cubicle type of structure the side wall effects must also be considered. This is done by determining the reflection coefficient which in turn determines the equivalent weight of the charge acting on the wall. Figure 3 - indicates graphically the method for determining reflection factors as a function of wall height, scaled distance from the wall in question as well as adjacent walls, and elevation of the charge from the ground. These reflection factors are utilized as multiplying factors to be applied to the weight of actual charge, thus obtaining an equivalent charge weight. For large charges close to the wall these reflection coefficients may be of relatively great magnitude. Therefore, failure to take them into consideration in calculation of the blast loads on the wall may lead to seriously inadequate design of a structure to withstand these loads.

We come now to consideration of wall responses. This is the most complex phase of the design procedure. The major portion involves analysis of response of the protective wall to the blast loads resulting from the donor explosion and to primary fragments resulting from the donor casing break up. Let us examine a schematic representation of these responses which is shown on Figure 4. The chart indicates that the wall can be affected either by primary fragments or by blast. Consider first the effects of primary fragment impact on the wall. Primary fragments can either perforate the wall and come out on the acceptor side with some residual velocity, they can be embedded in the wall resulting in spalling, or they can be embedded in the wall without causing any damage to the wall on the acceptor side, which is indicated by "no action" on the chart.

Because spalling caused by primary missiles produces secondary (concrete) fragments of extremely low velocity we can neglect these effects in most cases. On the other hand, the perforation of the protective wall by primary fragments may cause propagation in the acceptor charge if their mass and residual velocity are sufficiently high.

Figure 5 - relates the striking velocity of primary fragments with maximum penetration for various fragment sizes. Once the maximum penetration of a given size fragment is known we obtain the fragment residual velocity from the chart shown on Figure 6. This plot represents two ratios; namely, the ratio of the residual velocity to striking velocity vs the ratio of wall thickness to maximum penetration. In order for a fragment to have a residual velocity after penetration through the wall, maximum penetration indicated on the previous figure must be greater than the wall thickness.

We come now to examination of the blast effects on the wall. Response of the wall to blast effects in close-in detonations may be expressed in terms of several modes of wall failure which are shown on the flow chart (Figure 4). The blast striking the wall may cause spalling and punching, which in turn cause secondary fragments on the acceptor side of the wall. These fragments upon hitting the acceptor charge may cause it to detonate. Punching and flexural failure (failure due to the bending action of the wall or its shearing off at the base) can cause total destruction which in turn will produce secondary fragments. Leakage around and over the protective wall must also be considered. If personnel protection is required a wall must withstand the blast load completely, and this condition is indicated on the chart by "no action."

The various modes of wall failure and their relative importance in causing propagation in the acceptor charge will now be discussed in more detail. Figure 7 - is a photograph of part of a wall taken after an actual large scale test. A portion of the wall was punched out without causing complete collapse of the wall. Figure 8 - shows the mass and velocity of the punched out section as a function of donor charge weight and its distance from the wall. As an example we can see from this chart that a 500 lb. donor charge located approximately 4 ft. from the wall (corresponding to reduced distance Z = 0.5) will punch out a piece weighing 100 slugs (3200 lbs.) at the initial velocity of 225 ft/sec. Kinetic energy of this fragment equals 2,600,000 ft/lbs.

Figure 9 - is a similar plot relating mass, velocity and kinetic energy with charge weight for the spalling mode of wall failure. Under the same load conditions (500 lb. charge, 4 ft. from the wall) the corresponding values for mass, velocity and kinetic energy of the spall amount to 64 slugs (2100 lbs), 46 ft/sec., and 68,000 ft. lbs. respectively. Comparing these values with those obtained for punching it is clear that the propagation probability due to secondary fragments caused by punching is much greater than by spalling.

When total protection is required - such as for personnel or very specialized equipment - neither punching nor spalling can be tolerated. Figure 10 - relating charge weight with reduced distance indicates threshold conditions of non-occurrence of spalling for various wall thicknesses. Our studies have shown that if the wall is designed in such a way that no spalling occurs, then no punching will occur.

The next step in our analysis is investigation of flexural capacity of the wall. Flexural failure may be caused by bending action of the wall and/or its shearing off at the base. Figure 11 - represents incipient conditions of flexural failure for a cantilever wall. Here, the charge weight is correlated with the wall height for various wall resistance requirements expressed in terms of moment capacities (determined by reinforcement, concrete strength, and wall thickness) for the condition of incipient wall failure. For any point on the line of constant pressure leakage, relating minimum wall height with the donor charge weight, the intersection with a constant resistance line indicates the flexural failure threshold condition for the wall. For total protection the wall capacity must be greater than that for incipient failure conditions indicated on this chart. On the other hand, when protection against explosion propagation is the only requirement, wall collapse is tolerable as long as the secondary fragments do not become a new source of propagation of the acceptor charge.

The final step in our wall response analysis is the investigation of the total destruction mode of failure. Figure 12 - is a plot for determining kinetic energy which will be produced by failure of a wall due to punching, flexural failure or a combination of both, vs donor charge weight for various secondary fragment masses. Each chart is for a particular wall thickness and reduced distance. The mass distribution of these fragments will depend upon such factors as charge size and location, wall configuration (height, thickness, reinforcement, support conditions) and the properties of the concrete, while the fragment velocity will be governed by the fragment mass and the magnitude of the impulse load acting on this mass after break up. The properties of reinforced concrete cannot be completely defined due to its non-homogeneous nature, and therefore the velocity of the various fragments cannot be precisely predicted for a given condition. However, an estimate can be made of the average value of the maximum velocity of a particular size fragment formed upon collapse of the wall. The chart presented on Figure 12 is based on this estimate. We are particularly concerned with the size, velocity and shape of these fragments since recently run large scale tests indicate that the main cause for propagation of detonation is secondary fragments resulting from the total collapse of the wall.

This discussion so far has dealt with the standard reinforced cantilever walls. Charts similar to those shown have been developed for walls with two adjacent fixed edges and two free edges, walls with three fixed edges and free top edge, one way spanning walls restrained on both edges, and walls fixed on all four edges. In addition three basic types of wall construction were considered, namely:

1. Standard reinforced concrete wall.

2. Standard reinforced concrete wall with stirrups added.

3. Sandwich wall (two concrete walls with sand fill between them).

Lastly, we will consider the third major part in our overall design approach, the acceptor. Propagation into the acceptor charge could occur due to:

1. Blast effects developed by detonation of the donor explosive.

2. Primary fragment impact resulting from the break up of the donor casing.

3. Secondary fragment impact resulting from spalling, punching and/or flexural failure of the wall.

Blast and primary fragment effects were investigated in earlier work by Picatinny Arsenal. These finding were presented, as mentioned before, at the two previous meetings of the Loading Section. However, the large scale tests performed at Naval Ordnance Test Station, China Lake, California and other installations indicate that the most probable cause for propagation of detonation on the acceptor side of a protective wall is secondary fragments resulting from the break up of the wall. No data are currently available which would indicate the threshold velocities, masses, energies etc. of the secondary fragments necessary to cause detonation in the acceptor charge. Our planned confirmatory test program, therefore, includes tests to determine these criteria.

In conclusion, we feel that the Safety Design Criteria program represents a major and long needed step forward, which will result in far reaching and continuing benefits to all services and defense agencies with respect to:

1. Permitting most effective use of existing storage and manufacturing facilities.

2. Minimization of construction costs for new facilities and missile launching sites.

FIGURES

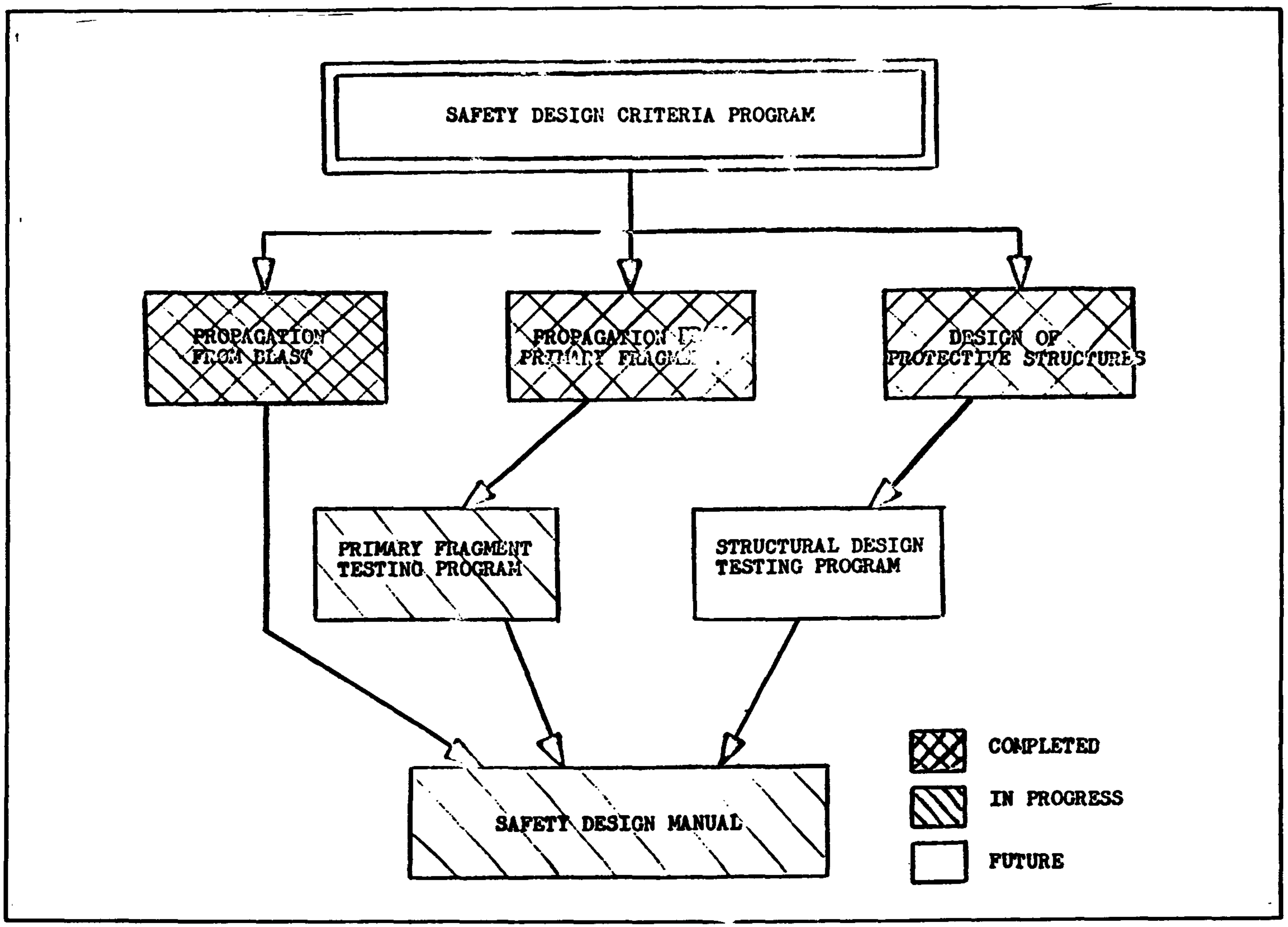
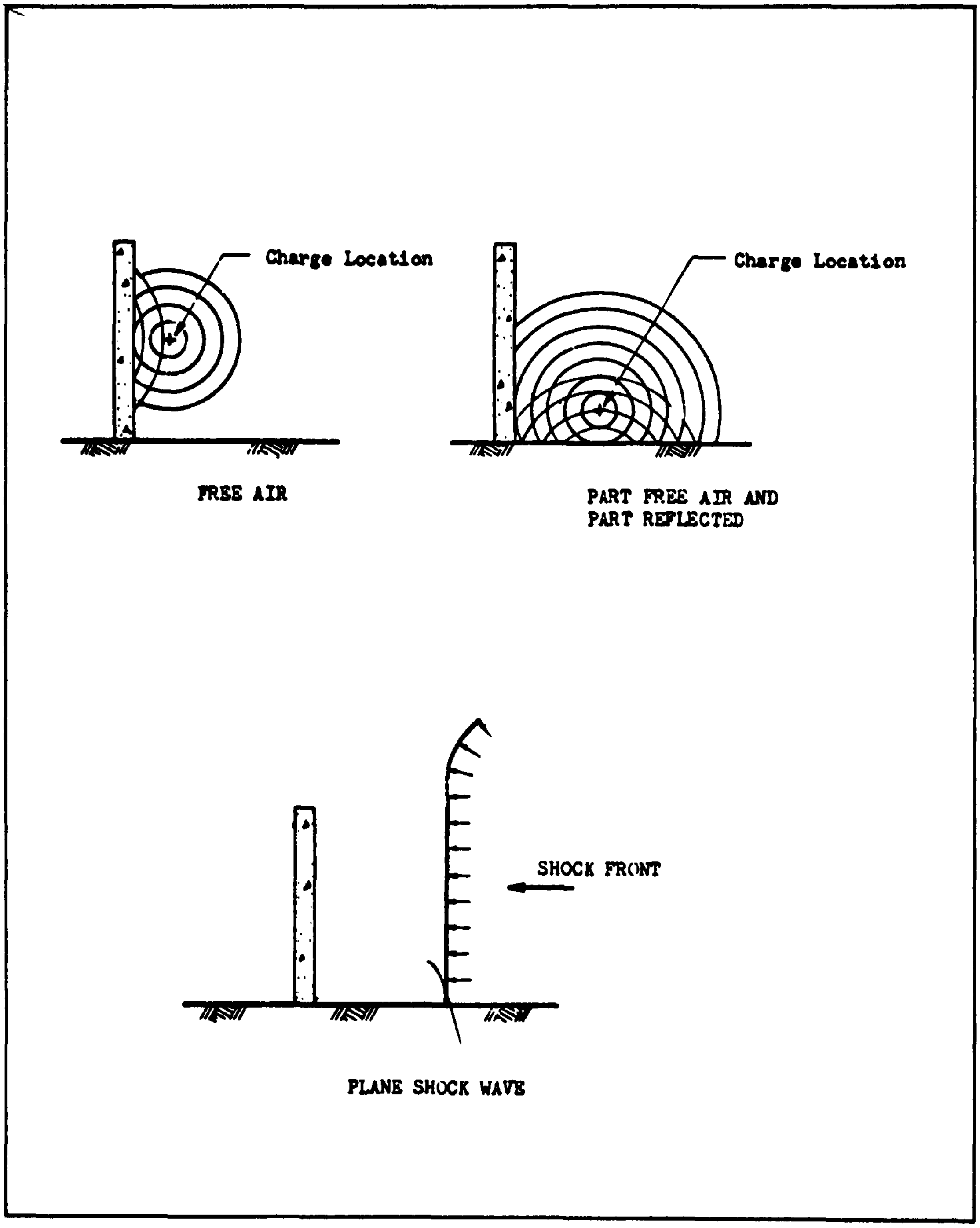
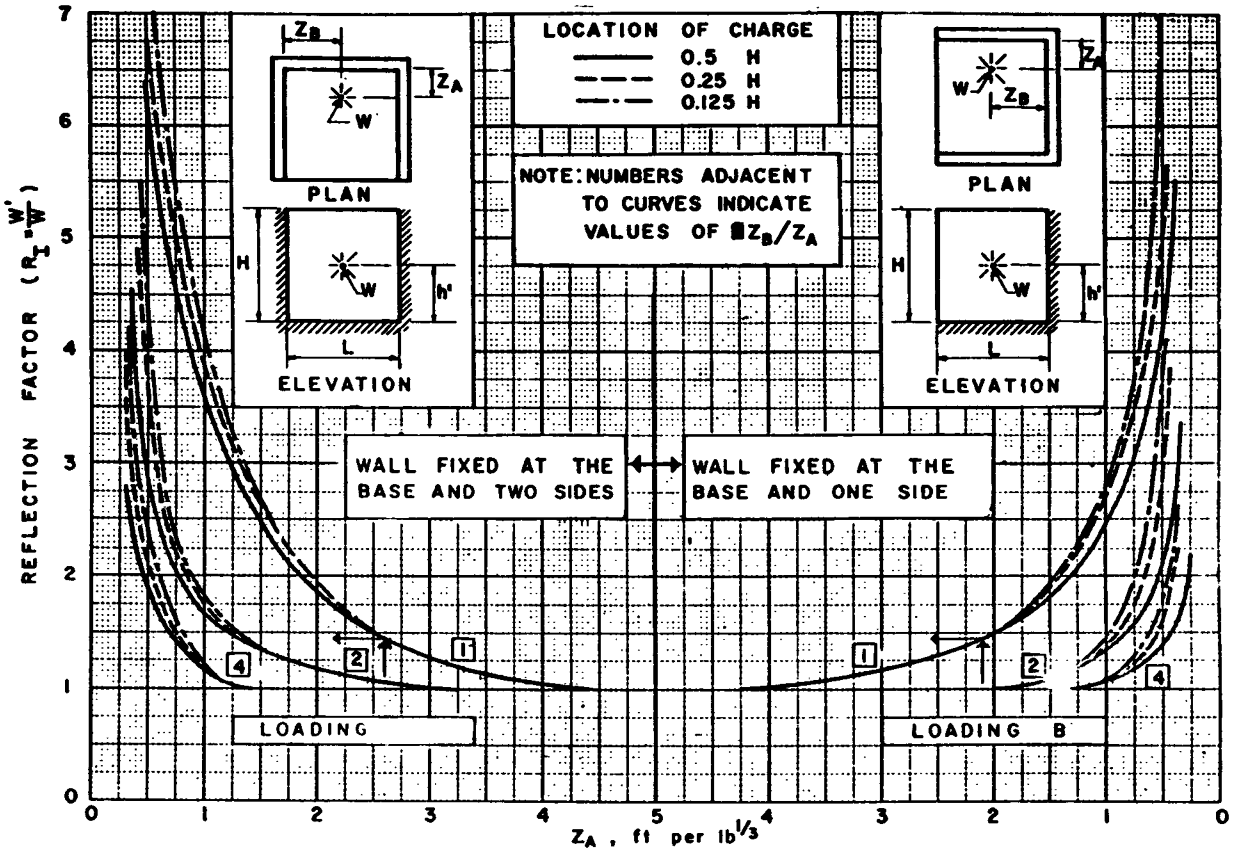

SAFETY DESIGN CRITERIA PROGRAM
PROPAGATION
FROM BLAST
PROPAGATION
DESIGN OF
PROTECTIVE STRUCTURES
PRIMARY FRAGMENT
TESTING PROGRAM
STRUCTURAL DESIGN
TESTING PROGRAM
SAFETY DESIGN MANUAL
COMPLETED
IN PROGRESS
FUTURE

Figure 1



Charge Location
Charge Location
FREE AIR
PART FREE AIR AND
PART REFLECTED
SHOCK FRONT
PLANE SHOCK WAVE

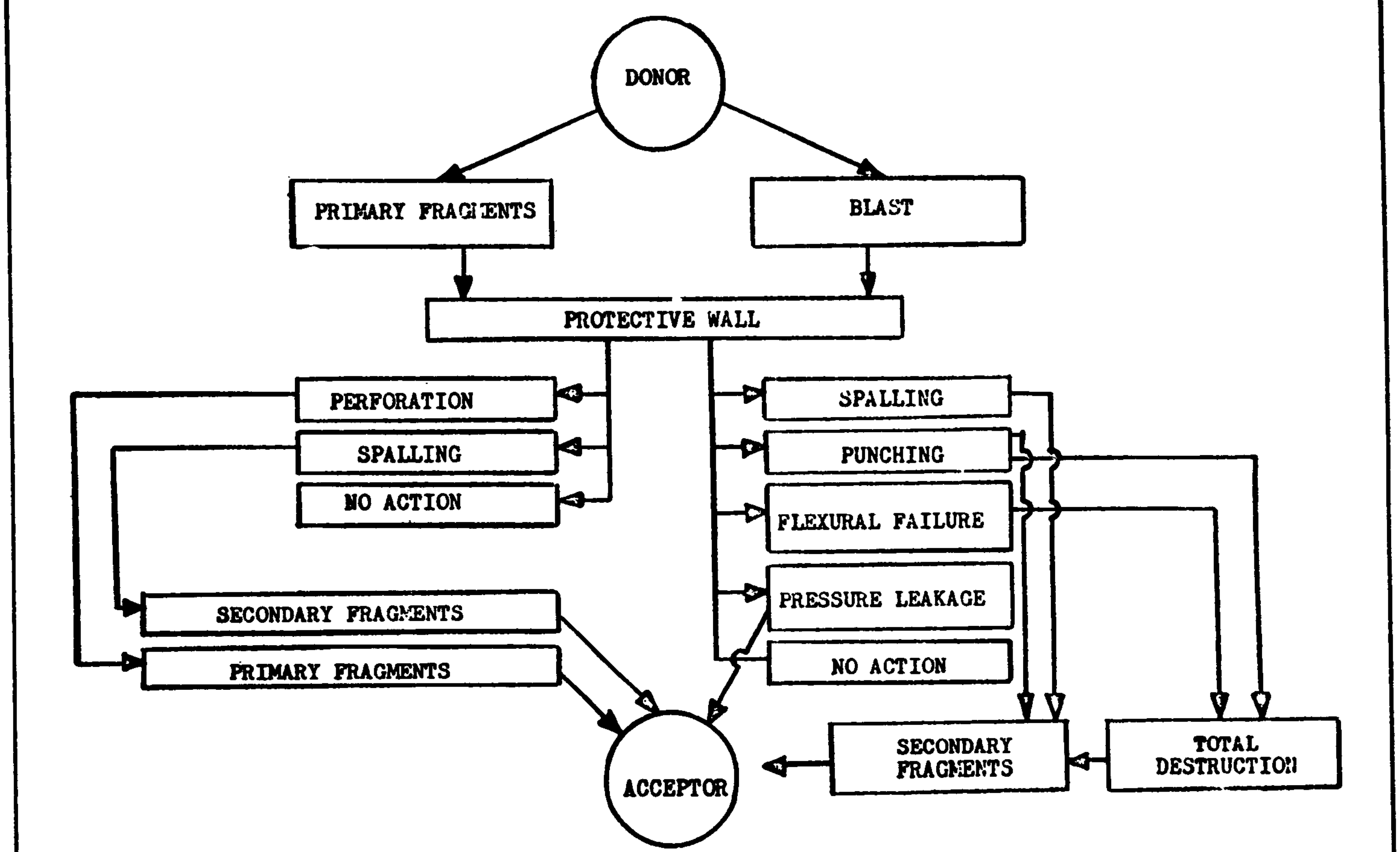
Figure 2



REFLECTION FACTORS FOR CUBICAL TYPE STRUCTURES

($L = H$ AND $\frac{L}{Z_B W^{1/3}} = 2$)

Figure 3



DESIGN OF PROTECTIVE STRUCTURES

Figure 4

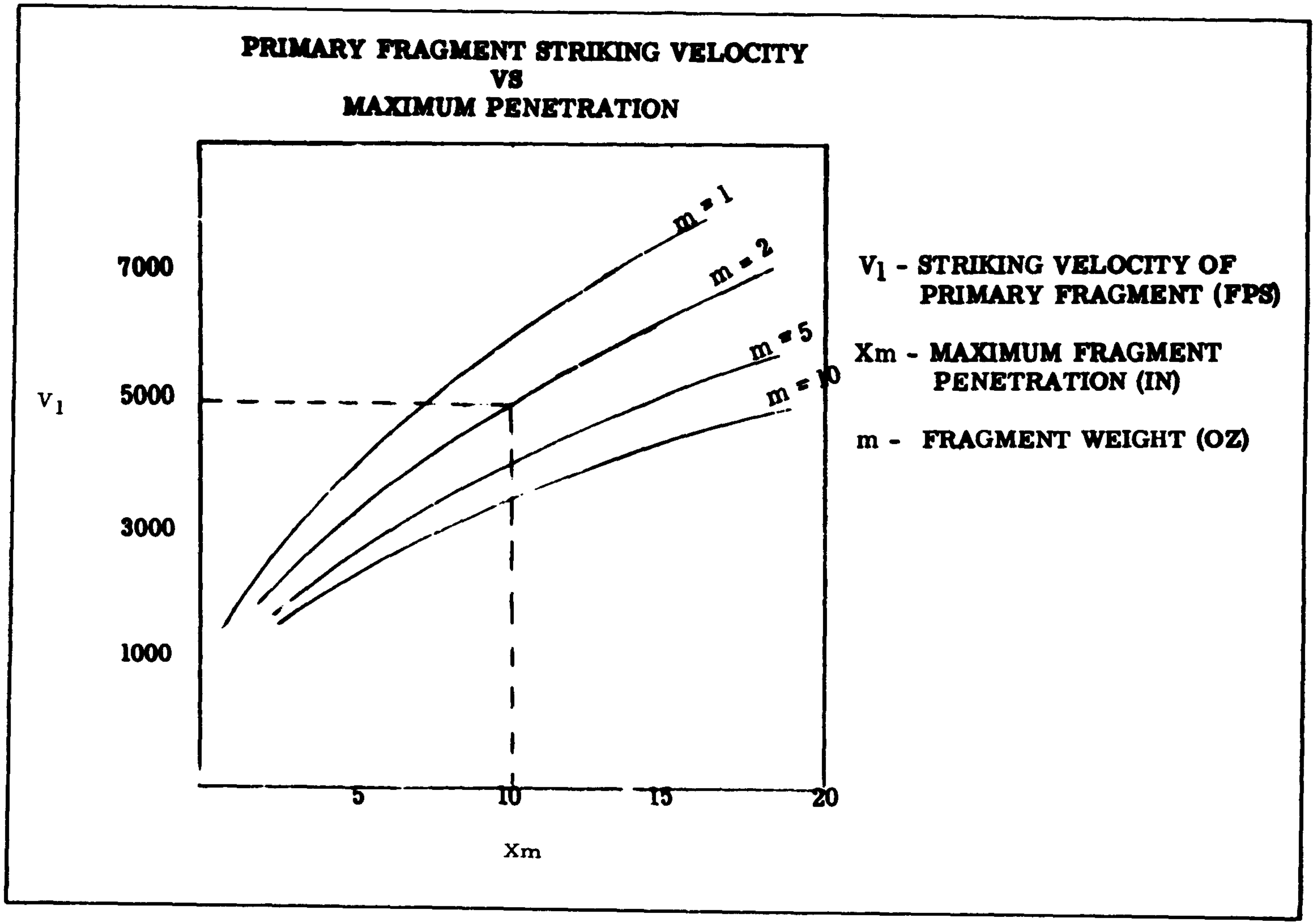

PRIMARY FRAGMENT STRIKING VELOCITY
VS
MAXIMUM PENETRATION
7000
5000
3000
1000
V_1
5
10
15
20
Xm
m = 1
m = 2
m = 5
m = 10
V_1 - STRIKING VELOCITY OF PRIMARY FRAGMENT (FPS)
Xm - MAXIMUM FRAGMENT PENETRATION (IN)
m - FRAGMENT WEIGHT (OZ)

Figure 5

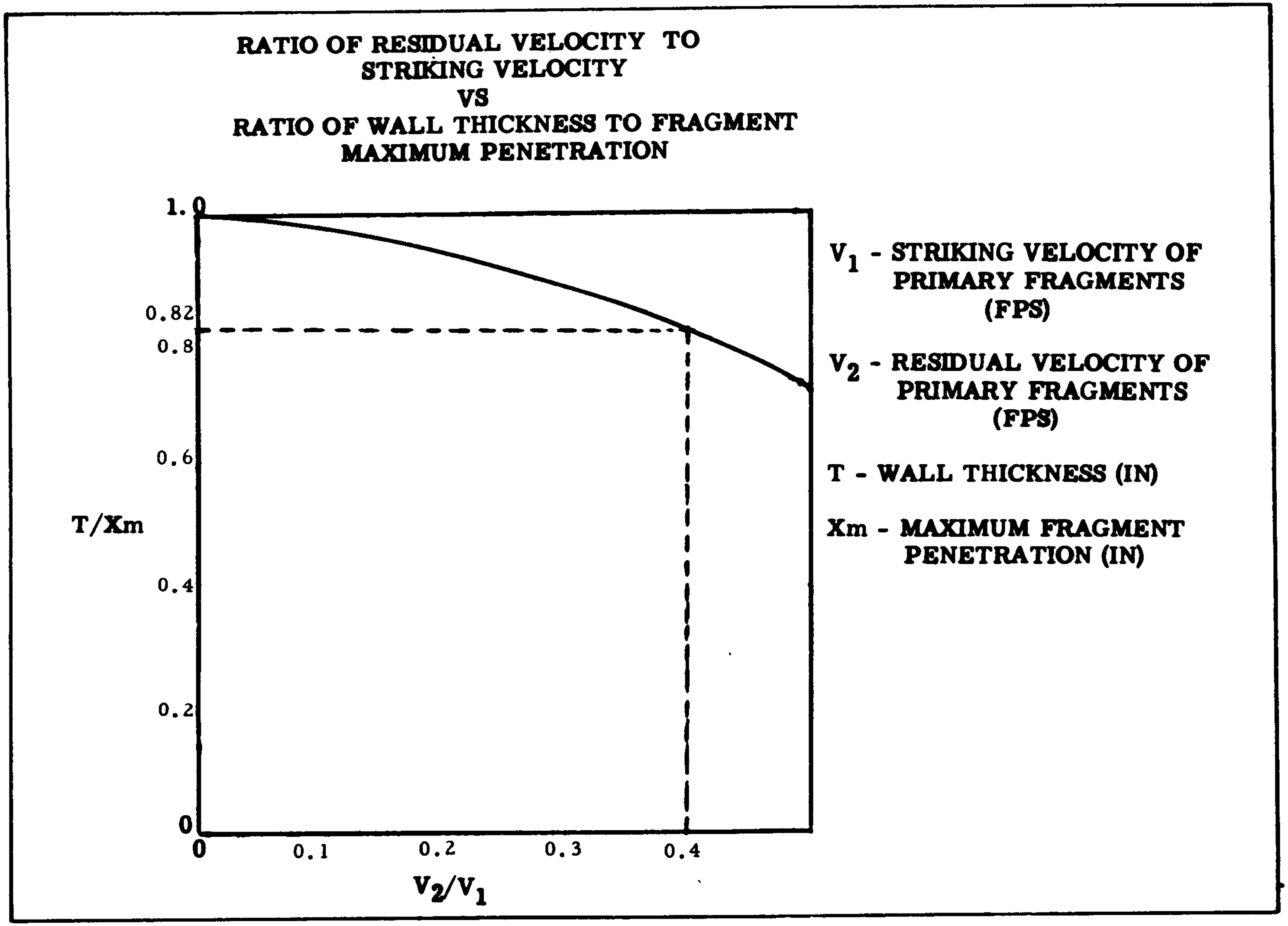

RATIO OF RESIDUAL VELOCITY TO
STRIKING VELOCITY
VS
RATIO OF WALL THICKNESS TO FRAGMENT
MAXIMUM PENETRATION
1.0
0.82
0.8
0.6
0.4
0.2
0
T/Xm
0
0.1
0.2
0.3
0.4
V2/V1
V1 - STRIKING VELOCITY OF PRIMARY FRAGMENTS (FPS)
V2 - RESIDUAL VELOCITY OF PRIMARY FRAGMENTS (FPS)
T - WALL THICKNESS (IN)
Xm - MAXIMUM FRAGMENT PENETRATION (IN)

Figure 6

Figure 7

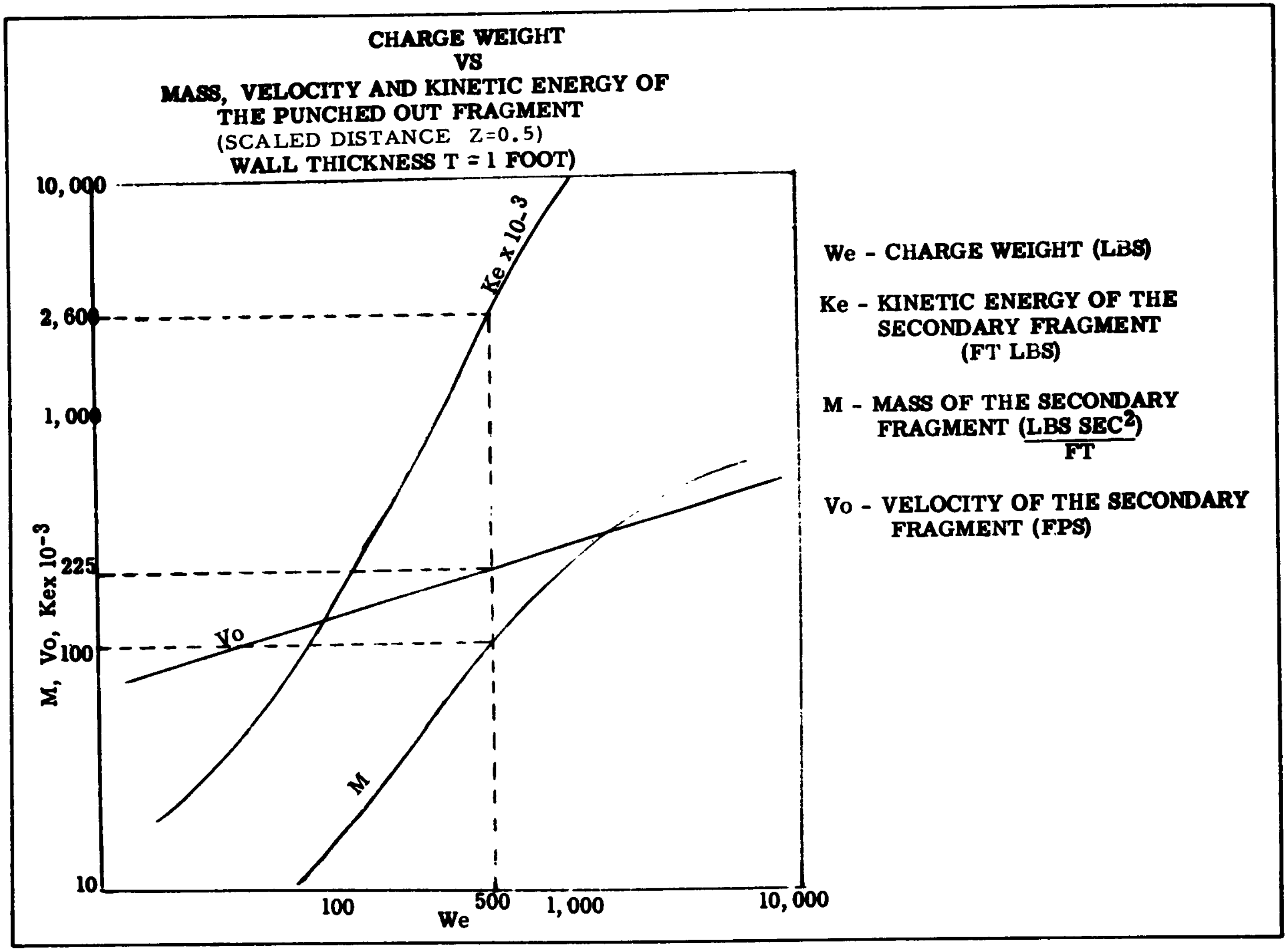

CHARGE WEIGHT
VS
MASS, VELOCITY AND KINETIC ENERGY OF
THE PUNCHED OUT FRAGMENT
(SCALED DISTANCE Z=0.5)
WALL THICKNESS T = 1 FOOT)
10,000
2,600
1,000
225
100
10
M, Vo, Kex 10-3
Ke x 10-3
Vo
M
100
500
1,000
10,000
We
We - CHARGE WEIGHT (LBS)
Ke - KINETIC ENERGY OF THE SECONDARY FRAGMENT (FT LBS)
M - MASS OF THE SECONDARY FRAGMENT (LBS SEC2 / FT)
Vo - VELOCITY OF THE SECONDARY FRAGMENT (FPS)

Figure 8

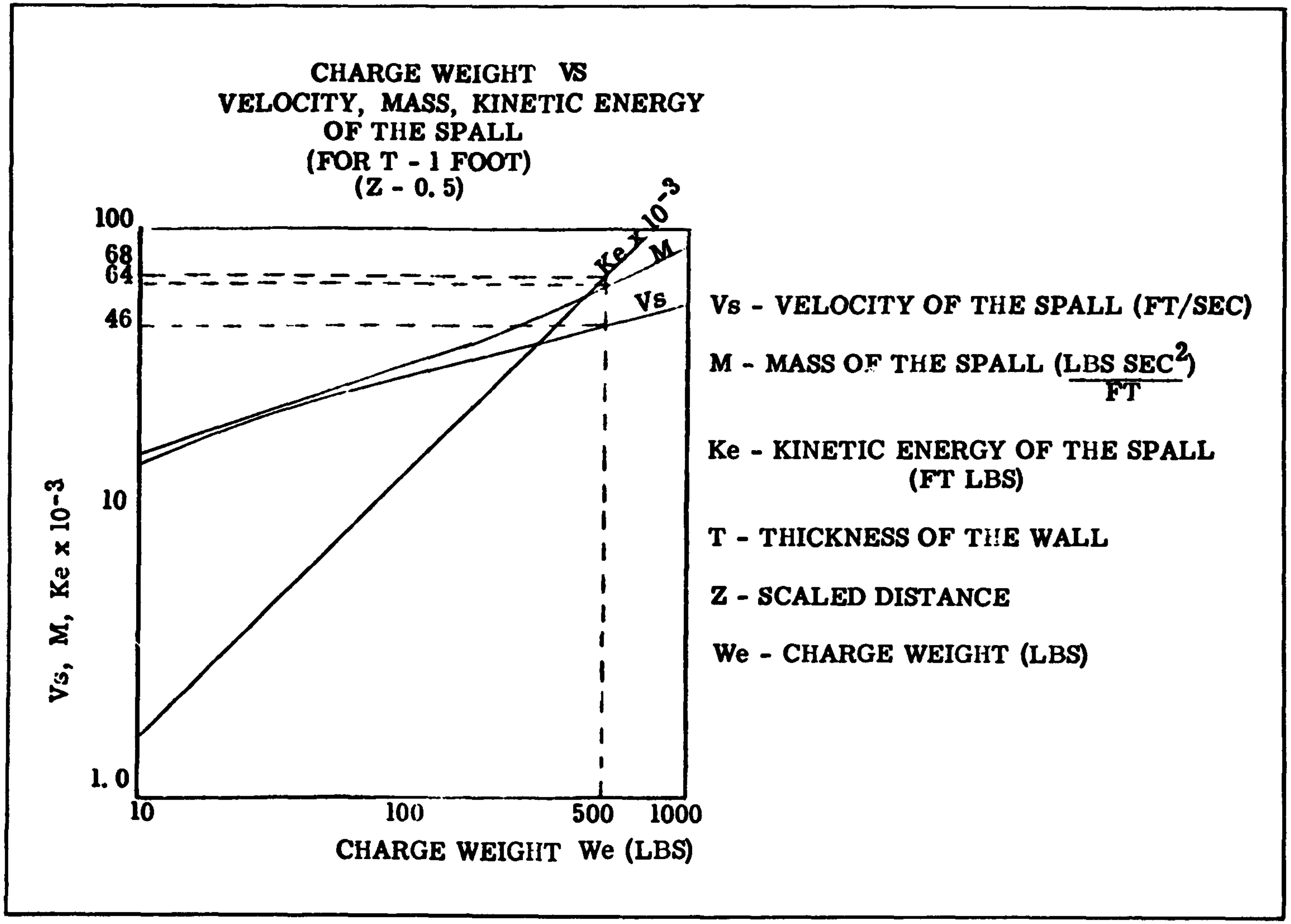
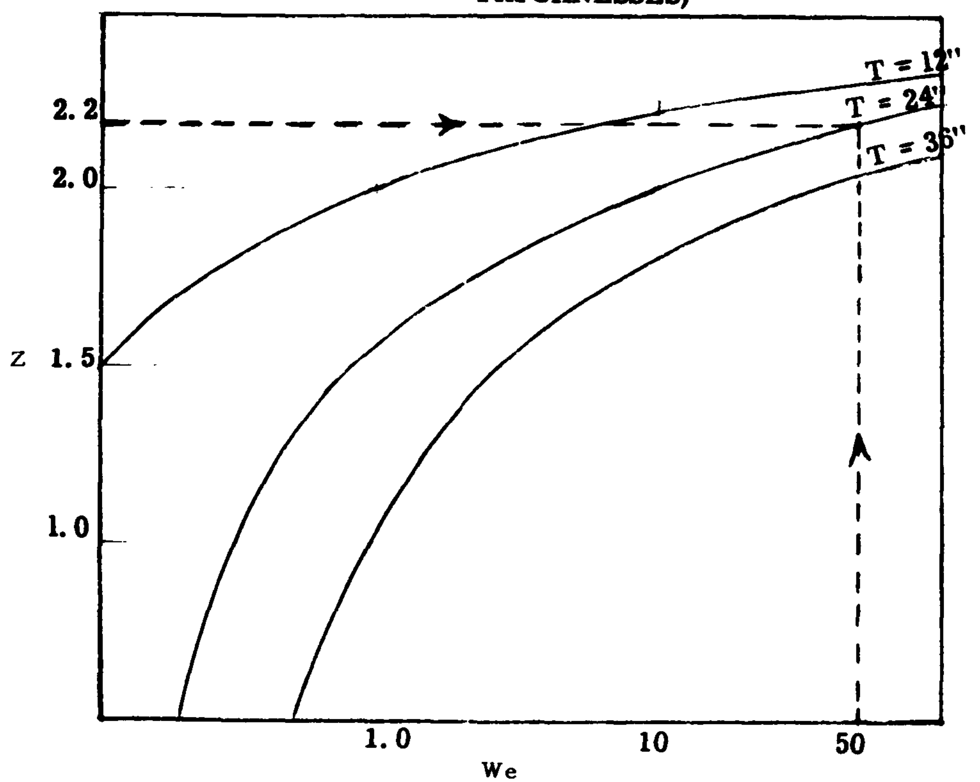

CHARGE WEIGHT VS
VELOCITY, MASS, KINETIC ENERGY
OF THE SPALL
(FOR T - 1 FOOT)
(Z - 0.5)
100
68
64
46
10
1.0
10
100
500
1000
CHARGE WEIGHT We (LBS)
Vs, M, Ke x 10-3
Ke x 10-3
M
Vs
Vs - VELOCITY OF THE SPALL (FT/SEC)
M - MASS OF THE SPALL (LBS SEC2/FT)
Ke - KINETIC ENERGY OF THE SPALL (FT LBS)
T - THICKNESS OF THE WALL
Z - SCALED DISTANCE
We - CHARGE WEIGHT (LBS)

Figure 9

CHARGE WEIGHT
VS
SCALED DISTANCE (FOR VARIOUS WALL THICKNESSES)



We - CHARGE WEIGHT (LBS)

Z - SCALED DISTANCE ($FT/LB^{1/3}$)

T - WALL THICKNESS (IN)

Figure 10

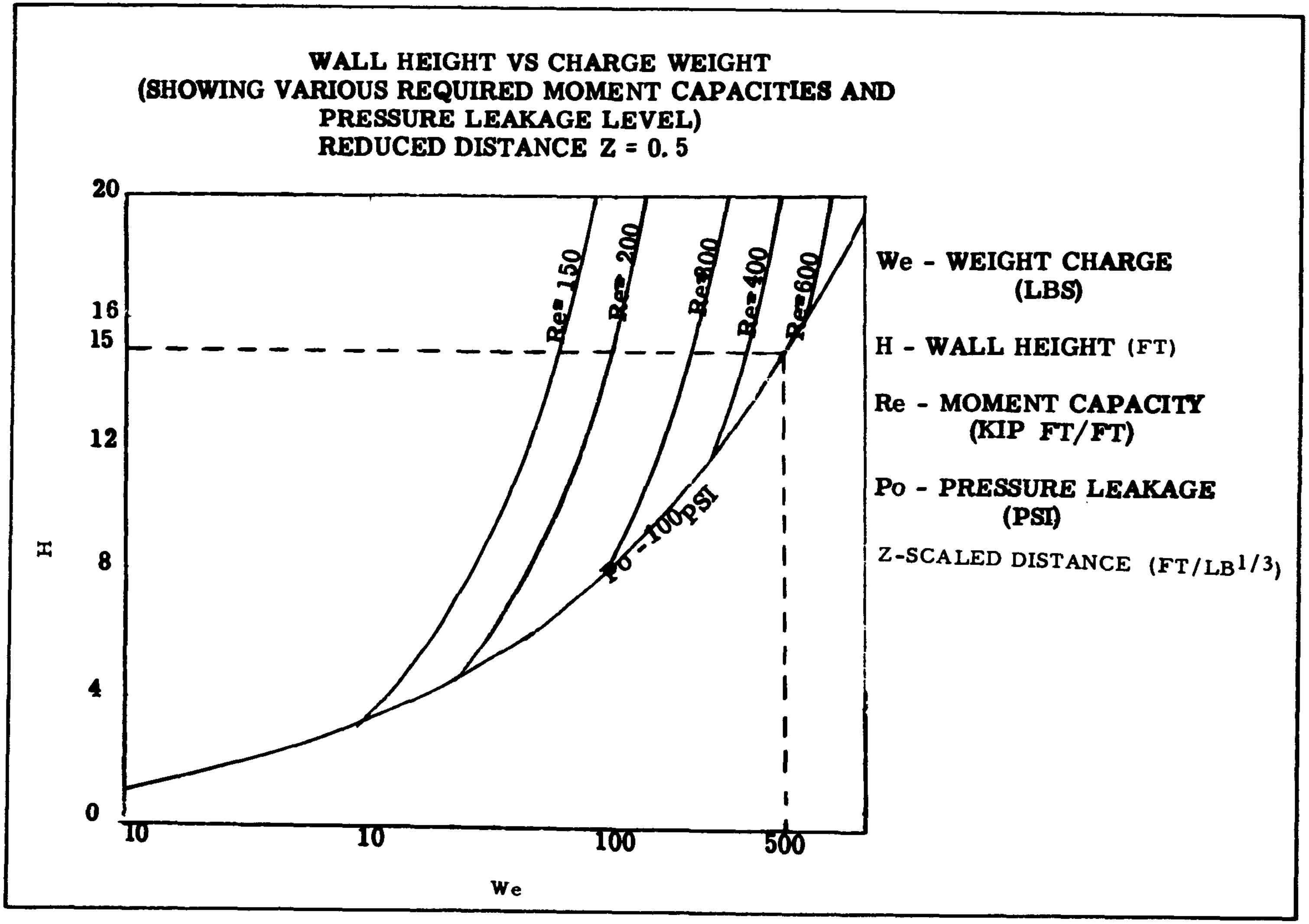
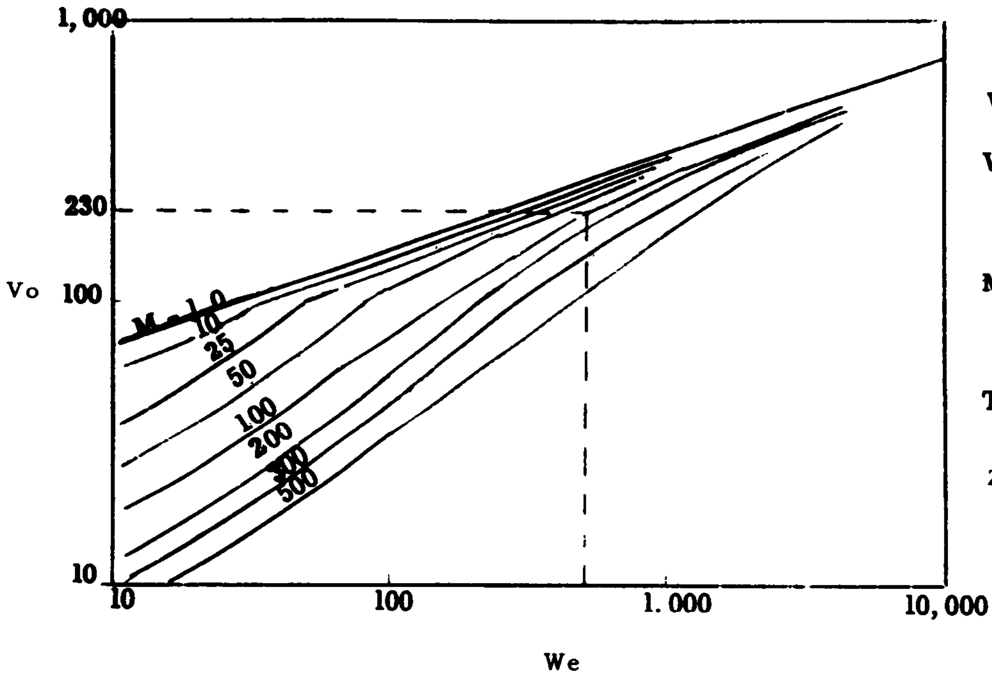

WALL HEIGHT VS CHARGE WEIGHT
(SHOWING VARIOUS REQUIRED MOMENT CAPACITIES AND PRESSURE LEAKAGE LEVEL)
REDUCED DISTANCE Z = 0.5
20
16
15
12
8
4
0
H
10
10
100
500
We
Re= 150
Re= 200
Re=300
Re=400
Re=600
Po - 100 PSI
We - WEIGHT CHARGE (LBS)
H - WALL HEIGHT (FT)
Re - MOMENT CAPACITY (KIP FT/FT)
Po - PRESSURE LEAKAGE (PSI)
Z-SCALED DISTANCE (FT/LB1/3)

Figure 11

TOTAL DESTRUCTION CHART
CHARGE WEIGHT
VS
VELOCITY OF SECONDARY FRAGMENTS FOR VARIOUS FRAGMENT MASSES
(FOR T - 1 FT., Z = 0.5)



We - CHARGE WEIGHT (LBS)

Vo - VELOCITY OF THE SECONDARY FRAGMENTS (FPS)

M - MASS OF THE SECONDARY FRAGMENTS $\left(\frac{LBS\ SEC^2}{FT}\right)$

T - THICKNESS OF THE WALL (FT)

Z - SCALED DISTANCE ($FT/LB^{1/3}$)

Figure 12

ABSTRACT DATA

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Accession No.________AD________

Picatinny Arsenal, Dover, New Jersey

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Technical Memorandum 1144, March 1963
33pp, figures
Unclassified memorandum from the Process Engineering Laboratory, Ammunition Group

The development of design criteria for protective structures to prevent propagation of explosives into the acceptor charge and personnel injury is discussed.

The over-all design approach was divided into three separate areas -- donor effects, wall response and acceptor effects.

Since this presentation, certain revisions have been made to relationships used in the illustrative examples. However, these revisions do not alter the design principles discussed.

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1. Safety design criteria

I. Rindner, Richard M.
II. Saffian, Leon W.

UNITERMS

Safety
Design
Protective
Structures
Processing
Acceptor effects
Donor effects
Wall response
Personnel
Rindner, R.M.
Saffian, L.W.

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